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Surficial lineaments and their structural implications in the Williston Basin

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SURFICIAL LINEAMENTS AND THEIR STRUCTURAL IMPLICATIONS

IN THE WILLISTON BASIN

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This thesis submitted by Kirth Erickson in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota is hereby approved by the Faculty Advisory Committee under whom the work has been done.

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ABSTRACT

Lineaments of apparent geostructural origin are observable on air photos of the Williston basin. The pattern formed by these lineaments has the appearance of a broad system of interconnecting wrench faults such as occur on the adjacent Canadian shield. On this basis it is hypothesized that a broad system of left-lateral wrench faults may underlie the Williston basin region and possibly the entire continental foreland structural province.

Structures in the Williston basin are readily adaptable to this interpretation. The Nesson anticline appears to consist of a north-south realignment of a N. 40° E.- trending Precambrian high which was segmented by left-lateral, en echelon wrench faults and displaced to its present position. The Antelope anticline may be a drag fold associated with a major left-lateral shear zone. The Cedar Creek anticline is apparently the surface reflection of high angle reverse faulting along the southwestern edge of an elongate, N. 30° W. trending, crustal block which has tilted slightly basinward. Surface and subsurface studies support these interpretations.

Oil fields are offset across lineaments indicating that they may be the surface reflection of buried wrench faults. Lineaments also define permeability barriers which divide or terminate oil fields. These fields step down structurally toward the center of the basin indicating segmentation by faulting. Subsurface studies

indicate that the Paleozoic rocks in the Williston basin are more deformed than the overlying units and that closure on some structures increases with depth. Deformation related to faulting may be far more common than formerly suspected. Surficial lineaments reflecting this buried structure may provide a clue to the location of some prospective oil traps.

INTRODUCTION

General

The Williston basin is located in the heart of the North American continent and is centered just south of the U.S.-Canada border about 500 miles east of the Rocky Mountain front in northwestern North Dakota (Fig. 1). It lies within the continental foreland structural province (Sales, 1968) adjacent to the Canadian shield.

Known structures within the Williston basin consist essentially of the Nesson, Antelope and Cedar Creek anticlines. Structural anomalies have been drilled in various localities within the basin but only a vague picture of the general structure of the basin can be gained from the study of existing literature.

The purpose of this study is to develop a concept of the basic structural framework of the Williston basin. Hopefully, this will lead to the discovery of buried structural traps and ultimately oil accumulations.

Portions of the Williston basin in Montana, Saskatchewan and Manitoba were also investigated in order to develop a more complete concept of the underlying structural framework. The Canadian shield adjacent to the Williston basin in north Saskatchewan and Manitoba was also studied for the purpose of establishing an analogue of expected basement structures.

Figure 1.--The Williston basin is located in the center of the North American Continent.

Research Methods

Geophysical studies of various types including well logs, vertical magnetic intensities and gravity were used to infer the existence of various wrench faults. Surface studies done essentially while under the employ of Amerada Hess were also utilized. These include: investigation of the surface sag discussed by Royse (1967), discovery of the gravity fault on the crest of the Antelope anticline, the Souris River fault in southeastern Saskatchewan and northeastern Burke County (Hanson, 1960) and other localities where surface faulting is indicated.

Several flights were made over the area for the purpose of obtaining useful photographs but the light planes were limited to a ceiling of about 12,500 feet and insufficient altitude was gained to produce the necessary visual perspective. N.A.S.A's Goddard Space Flight Center, Greenbelt, Maryland, was contacted and satellite photos of the Williston Basin Region were obtained. These photos were Nimbus II and Nimbus III weather satellite remote sensor positives. The resolution was adequate for cloud cover, as designed, but far too poor to pick up anything but the largest lakes and streams on the surface. No other satellite coverage was available. As a result the North Dakota county index photo mosaics were used to trace out the through-going surficial lineaments. The mosaics were awkward to handle and the major lineaments were obscured by local detail. In order to reduce the resolution and eliminate all but the major lineaments the mosaics were reduced to a scale of approximately 1:1,000,000 and a mosaic of mosaics was constructed. The Bennie Pierre and Horse Creek lineaments in southwestern McKenzie County were discovered on this mosaic (Fig. 2).

The mosaic also assisted in establishing the spacial relationships and orientation of the various inferred faults in the area of the Nesson and Antelope anticlines.

Previous Work

The technique of relating surficial lineaments observable on air photos to subsurface structure was attempted only once in North Dakota to my knowledge. This study was done by Johnson (1960) relative to oil fields in the Burke County area. He concluded that a greater intensity of lineaments and fracture traces tended to correspond with areas of known production. Most lineaments in this area are glacial rather than tectonic.

Canadian geologists have been actively refining the techniques of lineament and fracture analysis for more than 10 years. According to Pamenter (1968, p. 20), "enough experience in checking lineations against subsurface structure has now been gained to leave no doubt as to their relationship." Haman (1964) has contributed an exhaustive discussion of these techniques to the literature. Other scientists such as Mollard (1957), Kupsch and Wild (1955), and Sproule (1962), to mention a few, have contributed much to the Canadian school of geostructural lineament analysis. Glacial, eolian, human, biologic and other factors confuse the tectonic picture. An attempt was made in this study to minimize the effect of local factors by mapping regional lineaments only.

THE CONTINENTAL FORELAND FAULT SYSTEM

The thesis of this paper is that a fault system 300 miles wide or greater may extend along the continental foreland from east-central Kansas into southern Saskatchewan and possibly from the coast of Florida to the edge of the continental shelf 500 miles northeast of Point Barrow, Alaska (Fig. 2). This fault system seems to underlie the Williston basin from at least the northeast edge of the Turtle Mountains on the continental side to the Cedar Creek anticline and beyond on the Cordilleran side. This fault system will be herein referred to as the continental foreland fault system or simply the Foreland fault system. Hunkins (1966, Fig.1) shows a 150-mile left-lateral offset at the projected intersection of this fault system with the edge of the continental shelf north of the Alaska-Yukon boundary.

Sales (1968, p. 10) stated that "the foreland is part of an integrated mechanical system that includes at least the eastern Pacific, the entire Cordillera from the Arctic to the Atlantic, and possibly much of the continental crust for at least 1,000 miles east of the Rocky Mountain front."

Moody and Hill (1956, p. 1241) concluded that, "(1) wrench faulting is much more prevalent than ordinarily supposed. (2) There exists a regmatic shear pattern common to the entire outer crust of the earth. (3) The major elements of this shear pattern are extremely large wrench faults which extend through the outer crust."

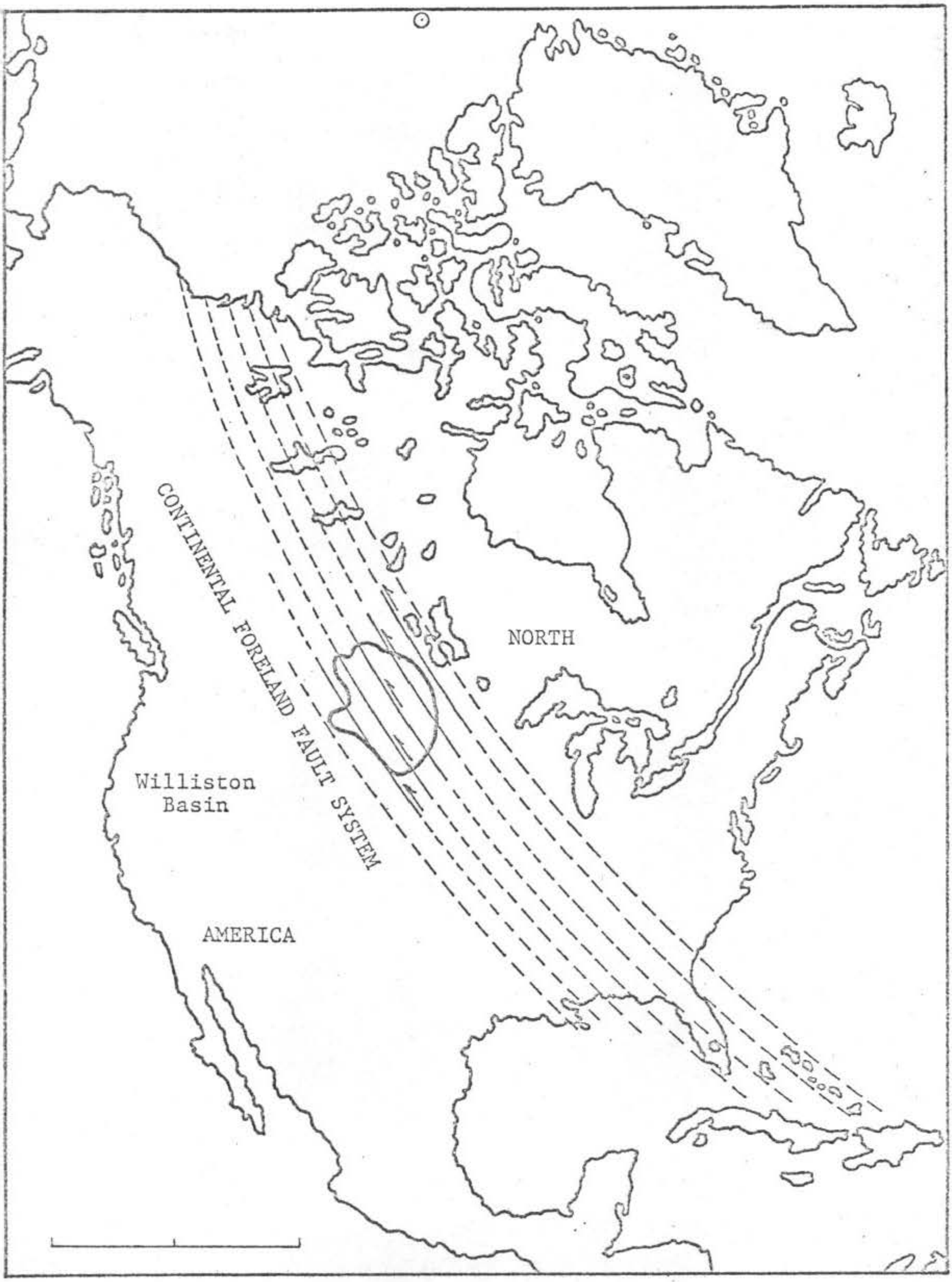

Figure 2.--The continental foreland fault system.

The continental foreland fault system, as interpreted from lineaments on air photos, trends approximately N. 40° W. and is characterized by broad shear-zones composed of left-lateral, en echelon wrench faults which bound crustal blocks ranging from a few miles to a few tens of miles wide. These blocks are occasionally transected by lineaments which trend about N. 50°E.

A similar fault system was documented by Coons, Woollard and Hershey (1967, p. 2381). They indicate that the mid-continent gravity high "extends from Lake Superior to Oklahoma and occupies the center of a 300-mile-wide fault system which crosses the center of the North American continent."

GEOSTRUCTURAL LINEAMENTS

Introduction

Geostructural lineaments are simply long narrow alignments of natural features on the earth's surface which are so arranged by influence of the underlying geologic structure.

Three basic categories of lineaments are observable on air photos: topographic lineaments, vegetal lineaments and soil-tonal lineaments (Haman, 1961). Each of these three categories of lineaments are expressed on air photos in the Williston basin.

Vegetal lineaments mark areas of thick top soil and different or greater water supply. Soil-tonal lineaments reflect differences in the underlying parent material and other factors. Topographic lineaments are defined essentially by the drainage pattern and joint system.

Boyer and McQueen (1964, p. 630) concluded that air photo linear features: "1. Are largely a reflection of fractures in the rocks, emphasized by vegetation and topography, 2. Have widespread distribution irrespective of rock exposures and thus afford a supplement to ground measurement, and 3. Are particularly useful for quickly determining major fracture (fault) trends for use in regional stress analysis."

Origin of Lineaments

The surface lineament pattern, according to Haman (1961), is the mirror image of a fracture system in the underlying bedrock.

Pamenter (1968, p. 18) states, "fractures tend to propagate themselves upward through each succeeding layer as it is deposited. . . . the result is a myriad of lineations which show up on aerial photographs."

Methods and factors of fracture origin are summarized by Haman. He lists earth tides, deep-seated tectonic movements, earthquake shocks, very deep-seated tangential compression, zones of local weakness that give rise to recurrent instability, intermittent movements along buried faults, crack propagation (by stoping), fatigue resulting from cyclic stresses, meridional stress forces, and adequate lengths of time for any or all of them to work.

Lineaments and Length

Lattman (1958) defines fracture traces as being less than one mile in length and lineaments as one mile or longer. He also points out that lineaments may be expressed either continuously or discontinuously.

The lineaments of Boyer and McQueen (1964) range from 1/4 to 4 miles in length. Haman (1961) defines three groups of lineaments: micro-fractures less than 1/10 of a mile long, meso-fractures 1/10 mile to 2 miles long and macro-fractures over 2 miles long. He draws the distinction on the basis of origin. The macro-fractures originated in the basement and reflect its structure. Meso-fractures originated in and reflect the structure of the overlying sedimentary rock column.

Some researchers dealing with shorter linear features prefer the term "fracture trace" because of the large scale implied by the word "lineament" (Boyer and McQueen, 1964).

"Besides alignments reflecting geological (bedrock) structure (which include joints, faults, and shatter zones associated with faulting) apparent fracture-trace features are produced by cultivation, paths and cattle trails, tertiary roads, drainage control features, or related cultural patterns." (Wobber, 1967, p. 502).

White (1961, p. 207) assigned the alignment of small intermittent stream channels to infilling of non-aligned stream segments by the prevailing wind in western South Dakota and "other plains states." This includes the southwestern corner of North Dakota. The dominant joint set in North Dakota trends N. 35 to 45°W. The prevailing wind direction is variable around N. 45 to 50°W. sub-parallel to the joints (White, 1961). Joint lineaments are very straight, narrow, and continuous across varying topography. Aeolian lineations are generally broader, discontinuous, interrupted by variations in local topography and irregular in outline (Fig. 3).

The shortest lineaments involved in this study are 5 miles long and range upward to several hundred miles. This eliminates most possibilities of any confusion with cultural lineaments with the exception of roads, railroads, pipe lines and power lines. These features have a very characteristic pattern which is easy to separate from the natural geostructural lineaments. Shorter lineaments are noted only where they appear to be short segments of discontinuous regional lineaments.

Moody and Hill (1956, p. 1214), in discussing recognition of wrench faults, indicated that "aerial photographs are of great assistance in identifying possible wrench faults by means of their straight traces."

Figure 3.--Discontinuous lineaments in the badlands along the Little Missouri River in south-central McKenzie County, North Dakota, parallel the dominant regional structural trends. (For location of this region see Plate 1.)

According to Byers (1962, p. 40), two periods of major faulting occurred within the Canadian Shield adjacent to Saskatchewan. The first was late Precambrian, the second post-Devonian to Tertiary. The older fault traces are essentially obliterated by subsequent orogenic movements and erosion but the younger ones appear "as prominent topographic lineaments on aerial photographs."

Byers (1962), in his study of major faults in the western part of the Canadian shield, cited several examples. The known total length of the Ross Lake system in Saskatchewan is about 200 miles. The length of the Hanson Lake fault system is over 380 miles. The Birch Rapids-Wepusko Bay zone can be traced by means of several parallels, overlapping, very straight, topographic lineaments. The length of this zone is in excess of 200 miles. The Maurice Lake structure (Byers, 1962, p. 47) may be traced by "a series of well-developed topographic lineaments for a total length of 180 miles."

Lineaments of this magnitude are observable on air photos in the adjacent Williston basin. The Cedar Creek anticline is rectilinear for a distance in excess of 150 miles. The Coteau Escarpment, a bedrock escarpment mantled with glacial debris (Townsend, 1950), runs several hundred miles from western Saskatchewan into eastern South Dakota.

The comparable length and orientation of lineaments in the Williston basin and on the adjoining portions of the Canadian shield suggest a similar origin.

Joints and Drainage

Field observations indicate that the drainage pattern may be partially controlled by the structural orientation of bedrock joints.

Joints are most easily observed in the caprocks of buttes in western North Dakota. Joints are also observable in badlands and other areas where much bedrock is exposed. The drainage pattern is observed to parallel the joint trend to some extent. This tendency of joints to capture runoff accentuates the joint pattern to some extent as implied by Folsom and others (1959).

For example, the parallelism inherent in joint sets is reflected by a strong parallelism of streams of equal order in the drainage pattern. The resulting system of interstream divides, in turn, reflects the parallelism of the drainage pattern and the underlying bedrock joints. Joints may be observed on air photos and in the field which are parallel to straight segments of streams and interstream divides. A given lineament may be a combination of discontinuous linear stream segments interrupted by discontinuous linear segments of interstream divides. This is common in the badland regions of North Dakota along the Missouri and Little Missouri Rivers (Fig. 2).

EARTHQUAKES AND FAULTS

Introduction

Van Hake and Cloud (1965, Fig. 1) show a series of earthquake epicenters, of destructive and near destructive intensities, occurring from northeastern Kansas across eastern Nebraska to east-central South Dakota (Fig. 4). This trend was extended to the northwest by the July 8, 1968 earthquake south of Bismarck, North Dakota. Two other earthquakes have been reported in North Dakota, one occurred at Hebron on April 30, 1927 and the other at Williston on October 26, 1946. The May 15, 1909 earthquake at Avonlea, Saskatchewan may represent a further extension of the same trend. Frazer and others (1935) mapped two faults, one on either side of the Avonlea epicenter (Fig. 4).

Earthquakes in the Williston Basin

The following six earthquakes have been reported in North Dakota and the immediate vicinity since 1909 (Plate 1):

1. Avonlea, Saskatchewan, May 15, 1909, intensity 9 on the Rossi-Forel scale. Location: 105°W., 50°N., the shock was felt over an area of 500,000 square miles which would include all of North Dakota (Heck, 1928).

2. Hebron, North Dakota, April 30, 1927, intensity 2 on the Rossi-Forel scale. P. S. Jungers reported: "felt by one; fairly rapid, trembling and rocking, mostly east-west; pictures moved,

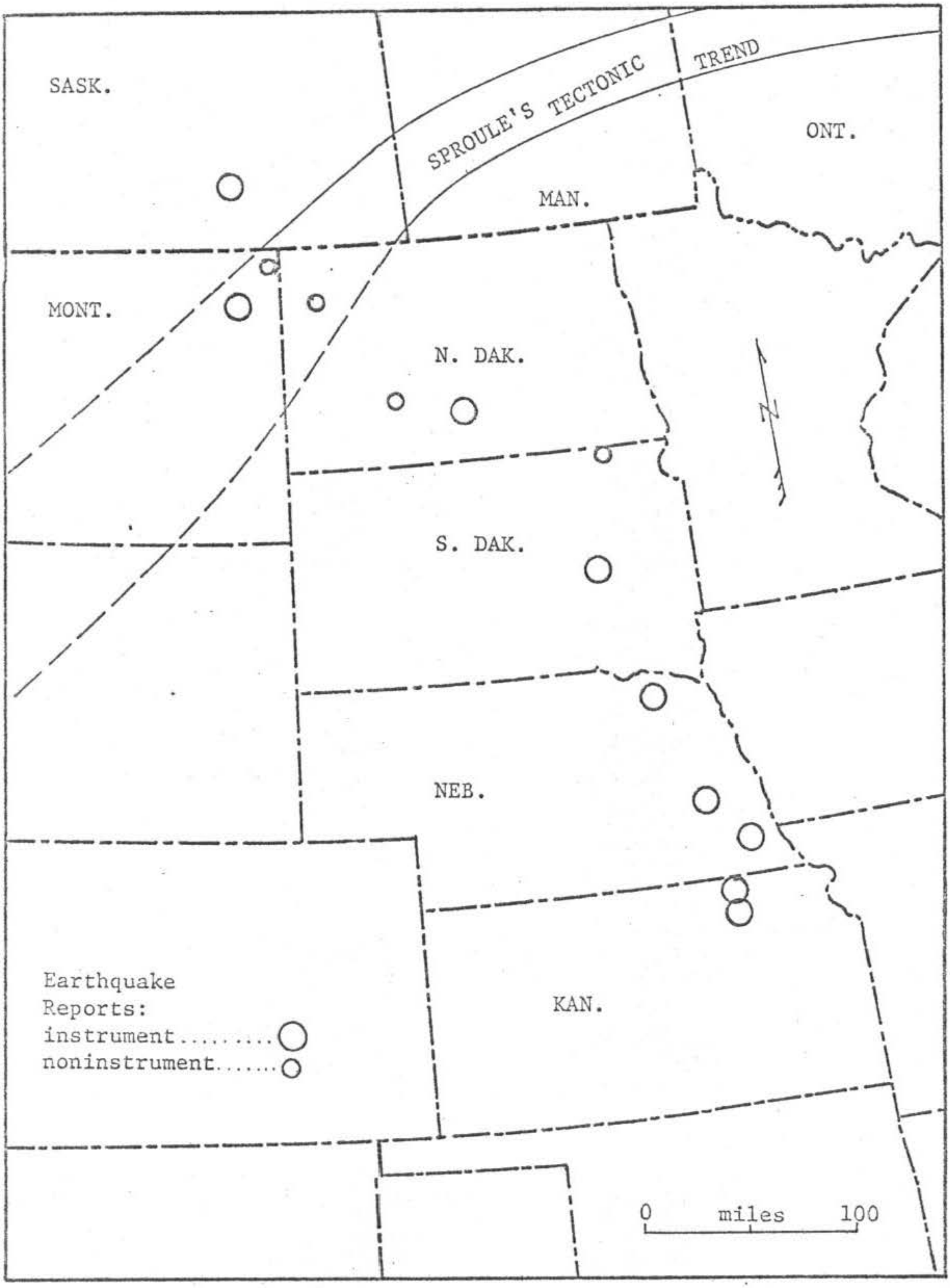

Figure 4.--Mid-continent earthquake epicenters. (Adapted from van Hake and Cloud (1965).)

hanging lights swung, plaster, table legs, etc., creaked" (Newman, 1930, p. 6).

3. Newark, South Dakota, January 29, 1934, intensity III on the Mercalli Scale. "Awakened several; dishes rattled; rumbling sound" (Newman, 1936, p. 9).

4. Southern Sheridan County--eastern Roosevelt County, Montana, June 24, 1943. Intensity VI earthquakes were felt at Froid, Homestead, Redstone and Reserve. Intensity IV earthquakes were reported from Medicine Lake and McCabe. Bodle (1945, p. 9) stated, "The shock was felt strongest around Homestead and Froid.

Froid.--Felt by many. Buildings swayed slightly and creaked. A well-constructed granary cracked so severely that wheat spilled out. The report from this town stated: 'One man north of Brockton was outside when it occurred. He said it felt as though the earth was heaving up and down.'

Homestead.--Felt by many. Faint subterranean sounds heard. Houses creaked and chandeliers swayed. Basement walls reported cracked.

Redstone.--Chandliers swung, chimneys cracked.

Reserve.--Two shocks. Thunderous, roaring subterranean sounds. Many cracks in plaster. Chimneys damaged."

5. Williston, North Dakota and Plentywood, Montana, October 26, 1946, intensity IV on the Mercalli scale. "Light shock of about 5 seconds duration felt by many in vicinity. Also felt at Plentywood, Mont. No damage. At Williston beds swayed and dishes rattled" (Bodle and Murphy, 1948, p. 7).

6. Bismarck, North Dakota, July 8, 1968, intensity IV to V on the Mercalli scale, magnetude 4.4 on the Richter scale. The shock was felt over a 9,000 square mile area. The epicenter was near the town of Huff which is located on the west bank of the Missouri River about 15 miles southeast of Bismarck. "This was the first instrumentally located epicenter in North Dakota; based on readings from 7 seismograph stations, the location was computed at 46.50°N, 100.6°W" (Lander, 1969, written communication).

Faults and Shear Zones

Earthquakes are direct evidence of differential movement between two blocks in the lithosphere (brittle portions of the upper mantle and the crust to a depth of 700 km where deepest foci occur). Mollard (1957, p. 44) states, "it is commonly held that tensile fractures and transcurrent (strike-slip) faults exist in the vicinity of earthquake foci." Moody and Hill (1956, p. 1215) "believe that the large primary wrenches extend through the outer crust and thus are very deep and fundamental flaws in the crust." My study indicates that these epicenters represent a major left-lateral wrench fault or mega-shear of continental magnitude. This shear zone is herein referred to as the Bismarck shear zone.

Sales (1968, p. 18), in reference to similar deeply buried wrench faults, states that "in the basement, such a wrench may be a distinct shear but by the time it has been propagated up to the surface it is a wide, distributively flexed zone." It runs from the southern end of the Beaverlodge oil field on the Nesson anticline at least as far as the South Dakota line southeast of Bismarck.

Subsurface indications for differential movement along this zone in Emmons County is indicated on plates 16, 17, 18 and 24 of Ballard's report (1963). This zone coincides with the line of earthquake epicenters mentioned in the previous chapter (Plate 1).

The configuration of geostructural lineaments as observable on air photos indicates that the Bismarck shear zone is offset to the west about 30 miles from the Beaverlodge field and continues from about 6 miles northeast of Williston to the Montana-North Dakota border (Plate 1). The offset zone herein referred to as the Williston shear zone, is characterized by high drainage density. This zone continues southeast of Williston as a narrow lineament running through the Blue Buttes oil field on the south end of the Nesson anticline. My observations indicate that many other lineaments in the Williston basin run parallel to these shear zones, but are discontinuous and otherwise less well defined.

The offset in the shear zone appears to be the surface reflection of the transfer of motion from the Bismarck shear zone to the Williston shear zone (Plate 1). The connection between the two is demonstrated in the discussion of the origin of the Antelope anticline later in this paper.

The northwest extension of the Bismarck zone is obscured by glacial sediments whereas the southeast extension of the Williston zone changes abruptly, at the intersection of the Yellowstone lineament (Plate 1), from a zone of high stream density to a narrow lineament.

Oil fields on the Nesson anticline are offset along the lineaments which define the hypothesized shear zones. The Beaverlodge field is offset to the northwest along the Bismarck shear zone from the Capa and Hofflund fields. A parallel offset occurs in the south end of the Blue Buttes field on the Williston lineament. These parallel offsets indicate that parallel wrench faults, providing they exist, would be offset in the same sense (left-lateral in this case).

Folsom and others (1959, p. 33) stated, "the assumption of faulting, as opposed to the direct method of logical contouring was made in view of the general situation on the Nesson anticline. Similar problems exist in all of the Nesson anticline fields. Many of the breaks between fields can best be explained by faulting. The suggested pattern (N. 37° W. to N. 53° E.) would fit well into the overall picture."

THE SHEAR PATTERN IN THE WILLISTON BASIN

The regmatic shear pattern divides the crust into polygonal blocks which are bounded by large wrench faults (Moody and Hill, 1956). In southeastern Saskatchewan "lineaments are regionally systematic and occur in great abundance" (Mollard, 1957, p. 6). Folsom and others (1959, p. 33) noted the gridded pattern in structural lineaments in North Dakota. "Of interest, also, was the configuration of the Little Missouri River in section 15, T. 148 N., R. 97 W. On aerial photographs, the bends of the river, at this point, form unusually sharp right angles, the bearings of the courses being parallel, and at right angles, to the assumed fault trace. The general configuration of the drainage pattern throughout the area would appear to follow a general grid pattern of bearings which are N. 37° W.- N. 53° E. (Plate 1).

Moody and Hill (1956) "concluded that major wrench faults, which penetrate the entire outer crust of the earth and result in wholesale segmentation of the outer crust into polygonal blocks, constitute a fundamental type of yielding in the crust." Cloos (1948) indicated that the earth's crust was divided into polygonal blocks of considerable depth during an early stage of its history.

The subtle surficial lineaments in the Williston basin betray such a polygonal pattern. The basic trends are N. 40 to 50° W. and N. 50 to 55° E. The dominant structural grain trends north-west-southeast parallel to the Williston and Bismarck lineaments. A subordinate set of lineations trend northeast-southwest parallel to the tectonic trend of Sproule (1962). The polygonal blocks in the Williston basin region may be bounded by faults paralleling these two shear trends. The dominant northwest trend reflects the left-lateral transcurrent faults of the Foreland fault system. The northeast-trending lineaments are possibly the surface expression of right-lateral transcurrent faults which parallel Sproule's tectonic trend (Plate 1).

MODES OF MOTION AND STRUCTURE GENERATING MECHANISMS

Introduction

The origins of most structures within the Williston basin may be attributable to minor movements on the master left-lateral wrench faults of the continental foreland fault system.

Movement associated with faulting is characterized by two basic modes: One is the sympathetic mode in which movement is parallel to the master fault, the other is the antithetic mode in which movement is non-parallel to the master fault (Billings, 1954, p. 208).

Minor differential movements between crustal blocks generate structures in the overlying sedimentary column by the following mechanisms.

Sympathetic Mode

1. Minor movements along pre-existing faults can result in surficial scarps. Moody and Hill (1956) indicate that the last increment of movement on wrench faults is essentially vertical. Byers (1962) cites many examples on the Canadian shield adjacent to the Williston basin in Saskatchewan.

2. Alternating subsidence of blocks results in horst and graben or basin and range topography (Billings, 1954, p. 203-211).

3. Reverse faulting due to tilting of a crustal block can result in a long linear anticline and a broad gently dipping

homocline (interpreted from subsurface studies on the Cedar Creek anticline and adjacent homocline sloping northeast).

4. Basinward tilting and en echelon subsidence of adjacent blocks can result in an en echelon series of homoclines overlying the blocks divided by monoclines overlying the interblock faults. (This mechanism may account for abrupt basinward thickening, often with accompanying facies changes, as observed in various sedimentary units within the Williston basin. These facies changes tend to be vertically stacked in the sedimentary column indicating intermittent basin subsidence (Ziebarth, 1969, oral communication).

Antithetic Mode

The following two mechanisms are stated for the left-lateral case; the reverse is true for the right-lateral case.

1. Right-handed transfer of motion, in which a given block moves faster than the block ahead, results in an uplift along the juncture, producing an upbulge or overthrust (Clayton, 1966, Fig. 2).

2. Left-handed transfer of motion, in which a given block moves slower than the block ahead, results in an opening between the blocks, into which overlying sediments subside, producing a sag or basin (Clayton, 1966, Fig. 2).

3. Lateral compression of a block adjacent to a shear zone may result in a drag fold, and related structures (Moody and Hill, 1956, p. 1214).

4. Compression within a shear zone may squeeze out a long thin sliver of rock resulting in a piercement structure (Wallace, 1949, p. 805 and Kingma, 1959, p. 15).

Implications of Modes and Mechanisms

Mechanisms of structure generation, as detected in the subsurface by geophysical techniques and on the surface by geostructural lineaments and topography, can be used to give otherwise unobtainable information about deep-seated fault geometry and movement (Clayton, 1966, p. 95).

Earthquakes reveal a mechanism in motion. They may accompany either mode. Logically the strongest shocks would occur in the sympathetic mode on the master faults. Location of the epicenter, or preferably the focus, with respect to the nearest master fault may give a clue as to the mode in operation.

Antithetic mode tends to disrupt the regional fracture pattern. Sympathetic mode tends to intensify the regional fracture pattern.

Antithetic mode produces non-parallel fractures in the overlying sedimentary column which are displayed on the surface as anomalies in the fracture pattern. These anomalies are observable on air photos by geostructural lineaments of anomalous length (includes meso-fractures of Haman, 1961) and orientation which confuse the pre-existing regional fracture pattern.

Sympathetic mode produces parallel fractures in the overlying sedimentary column which intensify the regional fracture pattern by increasing the surficial fracture density. These anomalies are detectable on air photos by broader geostructural lineaments producing unusual clarity of the regional fracture pattern.

ORIGIN OF STRUCTURES IN THE WILLISTON BASIN

Introduction

The following interpretations of the origin of various structures in the Williston basin are based on the mechanisms previously discussed and on the hypothesized existence of the continental foreland fault system with its characteristic left-lateral en echelon displacements on master wrench faults.

The major movements within the continental foreland fault system apparently occurred during the late Precambrian. These displacements may be reflected in the overlying sediments by anomalous structures, and on the surface by a confusing array of geostructural lineaments, due to reorientation of topographic and structural features, on the Precambrian surface which may have resulted from segmentation and dislocation along the shear zones. The only demonstrable example presently known is the Nesson anticline. The Burleigh High (Ballard, 1963) may be of similar origin (Plate 1).

Zone of Conspicuous Oblique Trends

A zone of conspicuous oblique trends include the upper Little Missouri River on the south of the study area and trends north-northeast to include the Moose Mountains in southeastern Saskatchewan (Plate 1). The Billings nose (Friestad, 1969) lies within this zone (Plate 1). The Billings nose parallels the eastern margin of the zone, then crosses over to the northwest in southern McKenzie County, and parallels the western margin of the zone. The Little Missouri River parallels the Billings nose into southern McKenzie County. Surface expression of this nose, although subtle, may have channeled the Little Missouri River and account, in part, for its original course.

The preglacial course of the Little Missouri crossed the Billings nose in southern McKenzie County and trended northeast in the direction of the Nesson anticline. At a point near Watford City the channel was diverted northward parallel to the Nesson anticline along the existing Tobacco Garden Creek. It evidently continued northward along the west edge of the Nesson anticline and was finally diverted northwestward into the preglacial Yellowstone River along the southern edge of the bedrock high formed by the Missouri Coteau. Field observations indicate that the divide was breached by diversion of glacially dammed waters through saddles along the crest. The interstream divides between the preglacial Missouri, Yellowstone and Little Missouri rivers all display this diversion characteristic (Howard, 1960, Plate 1). (The preglacial Missouri channel follows the Brockton-Froid fault zone) (Plate 1).

A cross trend between the Bismarck and Williston shear zones lies within this zone (the Antelope terminator fault). The Missouri Coteau is offset within the zone (Plate 1). The Souris River lineament (Kupsch, 1956) parallels the Coteau offset within the zone. The Moose Mountains lie within the northeastward extension of the zone. This feature effectively divides the Williston basin into two structural subprovinces. This zone may be the southwestward extension of the boundary between the Churchill and Superior structural provinces of the Canadian shield.

It is noteworthy that the east edge of the zone of oblique trends forms a drainage divide. The streams to the west of this line run northeastward paralleling the zone, whereas, those to the east trend essentially east-west. The dominant trend of the Churchill province south of latitude 55° N. is northeast. The dominant trend of the Superior province is east-west (Wilson and Brisbin, 1962).

Wilson and Brisbin (1962) discuss in detail the boundary zone between the Churchill and Superior provinces in Canada. The boundary is a fault which is bordered in the Superior province by a broad gneiss zone.

MacLaren and Charbonneau (1968, p. 65) indicate that the gneiss zone "has intermediate ages between the Churchill and Superior provinces and is considered to be Superior with an overprint of the Churchill orogeny." The Nelson River gravity high (Innes, 1960) approximately coincides with the gneissic belt.

The boundary fault corresponds with a strong gravity low (Wilson and Brisbin, 1962). MacLaren and Charbonneau (1968, p. 58) state, "a series of negative magnetic anomalies may coincide with a fault zone." No magnetic studies are available for the area west of the Nesson anticline.

A gravity study of northwestern North Dakota by Hanson (1960) shows two gravity lows to the west of the Nesson anticline. A weak low extends southward from the southeastern Saskatchewan low at Crosby, North Dakota, parallel to the Nesson anticline. A strong gravity low southwest of Grenora, North Dakota, near the Montana border, corresponds with the extension of the low from central Saskatchewan as shown by Wilson and Brisbin (1962, Fig. 2). Either of these lows may correspond to the boundary fault.

MacLaren and Charbonneau (1968, p. 58) state that, "the long axis of magnetic anomalies is parallel to the lineation, gneissosity, or foliation in the rocks which caused the anomaly," and that, "the granitoid rocks and highly altered gneisses generally correlate regionally with magnetic highs."

Goldich and others (1966) list two Precambrian cores from the Nesson anticline of <u>gneissic</u> composition and one of syenite. They cite Peterman and Hedge (1964) as attributing the low isotopic age determinations for these three samples to <u>alteration</u>. The Nesson anticline may then be a southward extension of the gneiss zone and the Nelson River gravity high. There is some possibility that the Billings nose may be a structural reflection of this same gneiss zone and represent the western border of the Superior province. The zone of conspicuous cross trends may then be a surface reflection of the area between the gneiss zone on the Superior province on the east, and the boundary fault between the two provinces, on the west. The gneiss zone is evidently weaker than the crustal rocks on either side and was squeezed up to form the long linear ridge which formed the preglacial drainage divide along the east edge of the zone.

Structural Origin of the Nesson Anticline

Three magnetic studies in the vicinity of the Nesson anticline from the Canadian border to 20 miles south of the Garrison Reservoir reveal offset anomalies at depth (presumably in the basement).

Hanson's (1960) vertical magnetic intensity map of Burke County shows an anomaly with a 4 mile left-lateral offset complete with drag configuration (Fig. 5). This offset corresponds to a surface lineament described by Kupsch (1956, Fig. 2) as a fault zone in southern Saskatchewan. This lineament extends east-southeast across northeastern Burke County to the vicinity of the Des Lacs River, where it is covered by till. The prominent air photo lineament defining this fault is located in a region of thick till indicating post-Pleistocene movement.

An earlier study by Hanson (1956) in the Tioga area shows a major offset in a magnetic high running approximately west-southwest between the Hoffland and Beaverlodge fields. This anomaly also demonstrates left-lateral displacement with drag configuration (Fig. 6). The displacement is from 7 to 8 miles. This offset corresponds to the Bismarck shear zone on the surface.

Opp's (1955) vertical magnetic intensity map of the Keene Dome shows still another magnetic anomaly with a left-lateral offset and drag configuration (Fig. 6). The displacement is approximately 3 1/2 miles. This feature corresponds to a discontinuous series of straight stream segments southwest of the Antelope anticline.

Mirchink and others (1968, p. 92) discussed a procedure for locating buried basement faults on young platforms in areas which are deeply subsided (more than 3 km). They conclude that "large . . . basement faults are . . . expressed most characteristically by the boundaries of magnetic zones with different kinds of anomalies and by abrupt gradients in magnetic field intensity."

These characteristics are in evidence in each of the three examples mentioned above. They are large, possibly broad shear zones

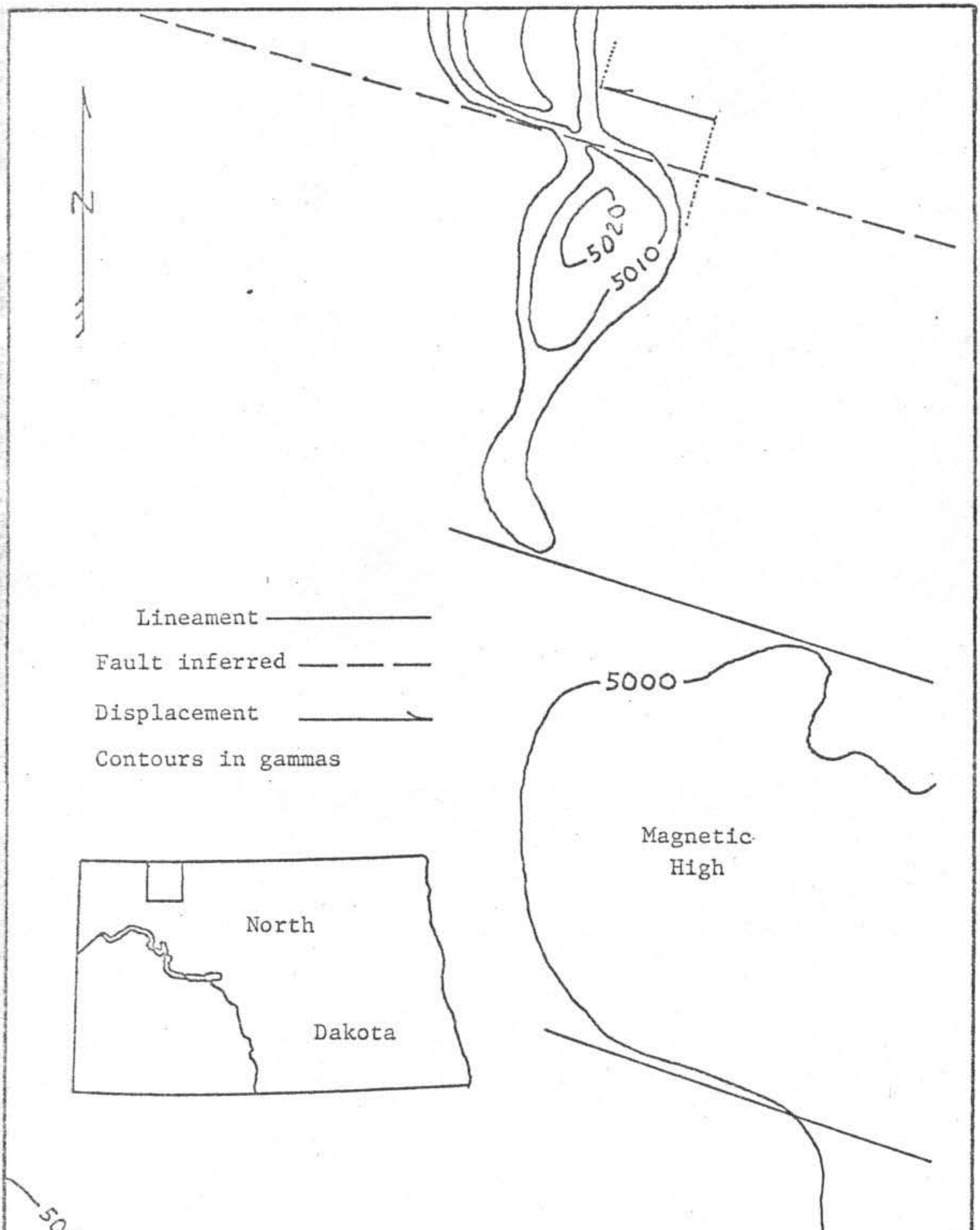

Figure 5.--The Burke County magnetic anomaly. (Adapted from Hanson (1960). Note well developed drag configuration adjacent to fault.

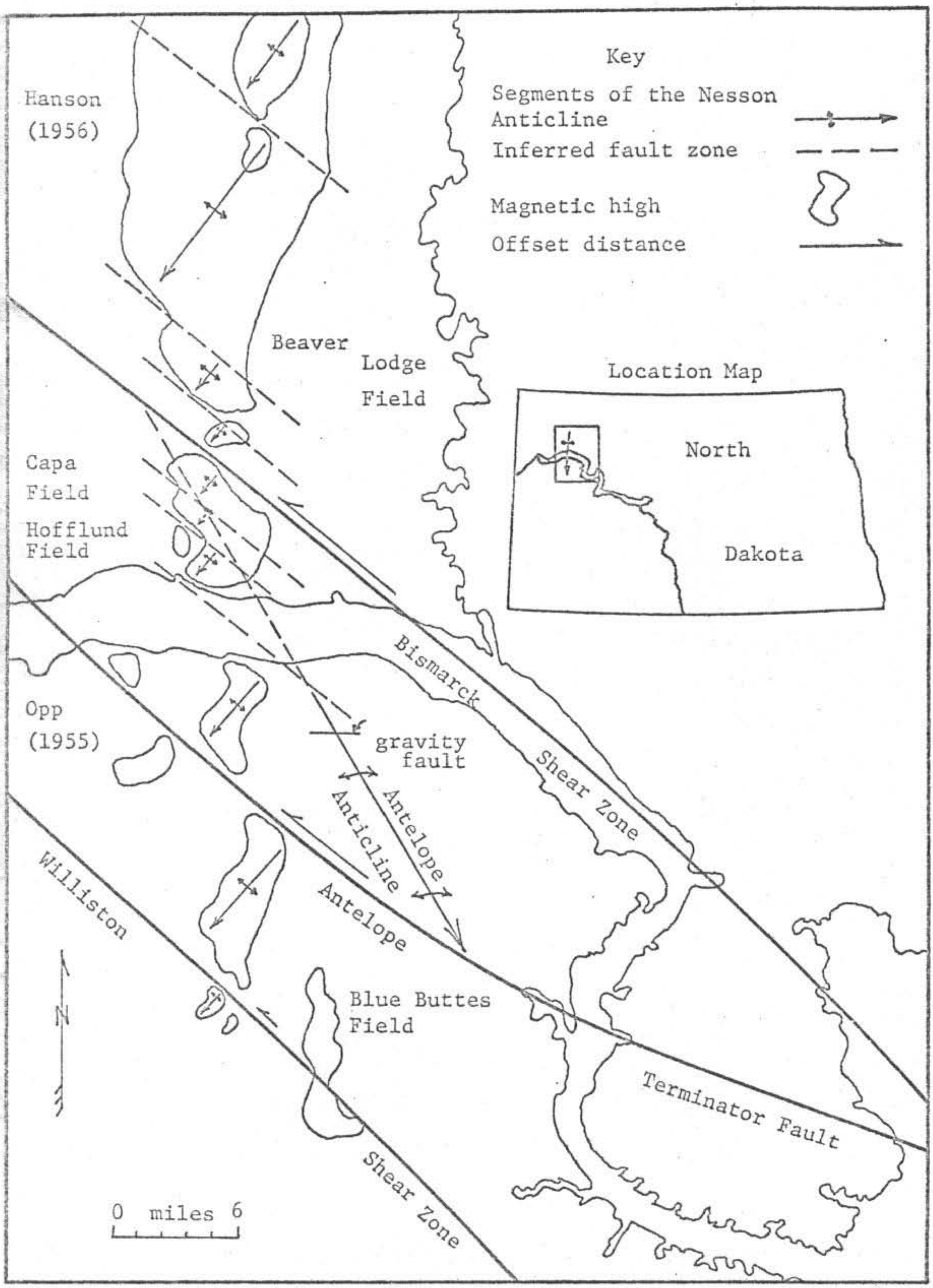

Figure 6.--En echelon offset segments of the Nesson anticline.

on transcurrent faults. They are deeply buried; Phanerozoic sediments are up to 15,000 feet thick in the area of these anomalies. They are bordered by abrupt gradients in magnetic intensity and the anomalies are offset in the same sense (left-lateral) across each lineament.

The Nesson anticline seems to consist of a series of en echelon segments of magnetic highs trending about N. 30°E. which have been displaced along the above described lineaments (shear zones) to form the north-south alignment observed on the present surface (Fig. 6).

This interpretation of the above described anomalies would indicate that a study of vertical magnetic intensity of the Blue Buttes field astride the Williston shear zone near the south end of the Nesson anticline should reveal a similar pattern.

A similar study in eastern Divide County may reveal the northward extension of the magnetic anomalies and the gneiss zone. A gravity study in the same area may reveal the southward extension of the Nelson River gravity high. Hopefully these would coincide.

The relatively undisturbed Phanerozoic sediments overlying these shear zones indicate that no major movements have occured since the Precambrian. Lineaments of regional extent in juxtaposition with these shear zones indicate that minor movements have been intermittent since the Precambrian.

A picture of this movement was obtained by comparing sequence (Sloss, 1963) thickness in a well on a Precambrian high (Carlson, 1960) with a well on either side (Table 1). These three wells are located in the southwestern end of the Beaverlodge field adjacent to the Bismarck shear zone (Plate 1).

TABLE 1

SEQUENCE THICKNESS IN THREE WELLS LOCATED ON A PRECAMBRIAN HIGH

Sequence	S.W. 1403	High 1231	N.E. 1385
		Well Number	
Tejas	?	?	?
Zuni	4810	4440	4925
Absaroka	840	835	770
Kaskaskia	4695	4685	4925
Tippecanoe	2225	2085	2225
Sauk	560	75	710
Precambrian			

Carlson and Anderson (1966) defined the sequences as described by Sloss (1963) for the Williston basin region.

The thickness of each sequence is less on top of the Precambrian high throughout the Phanerozoic Eon with the exception of the Absaroka sequence. This sequence indicates that the block northeast of the Bismarck shear zone was uplifted and less material was deposited on it or more was eroded from it. Both cases indicate uplift.

Persistent thinning on top of the Precambrian high indicates intermittent growth. In this regard Moody and Hill (1956, p. 1215) state "many individual pulsations can be dated by local unconformities or buttressing of individual stratigraphic units on growing drag folds." A detailed study of this nature on the Antelope anticline could reveal a wealth of information on tectonic activity in the Williston basin during the Phanerozoic Eon.

Structural Origin of the Antelope Anticline

The Antelope anticline is located in the northeast corner of McKenzie County, North Dakota. It projects from the east limb of the Nesson anticline like a thumb pointing to the southeast.

This anticline possesses all the criteria described by Moody and Hill (1956, p. 1214) for a drag fold associated with wrench faulting as follows:

1. "Drag folds should be asymmetric or overturned on the flank closest to the parent wrench."

Carlson and Anderson (1959, p. 12) state, " . . . the Antelope field is an asymmetric anticline trending north 40 degrees west, with either a steeper dipping limb or a fault on the northeast flank of the structure. (This steeper flank is adjacent to the Bismarck shear zone (Fig. 7). An alternate explanation is that the steeper dip on the northeast flank of the fold is due to faulting in the Precambrian basement. . . . if a fault is present its surface (plane) must be very highly inclined and must have been active intermittently with a gradually lessening effect through geologic time . . ." from Mississippian to late Cretaceous time.

Folsom and others (1959, p. 33) discussed at length the evidence for faulting along the steep northeast flank of the Antelope anticline. They cited A. F. Bateman Jr. and Charles E. Erdmann as indicating, that a field check had "revealed what we thought might be surface evidence of a fault." Bateman (1957) showed an inferred fault, which he called the Sanish fault, running along the steep flank of the anticline.

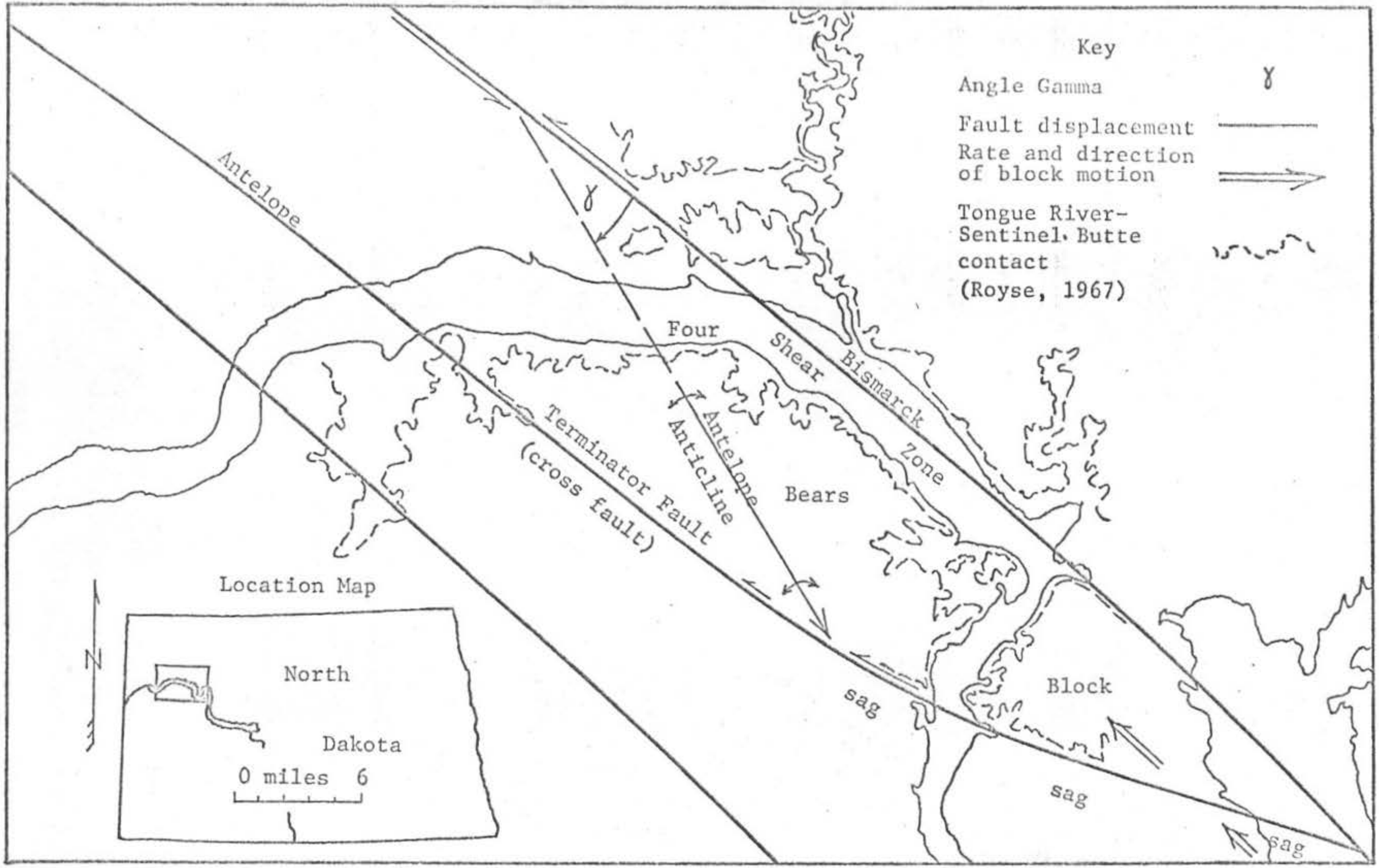

Figure 7.--Four Bears block and the Antelope anticline. The apex of angle gamma opposes the relative direction of motion of the Four Bears block with respect to the Bismarck shear zone.

2. "The apex of the angle gamma (the angle a drag fold forms with the parent wrench fault) should be opposed to the direction of lateral movement of the block" (Moody and Hill, 1956, p. 1214). The apex of angle gamma does oppose the relative direction of movement of the crustal block on which it rests (Fig. 7).

3. "Structures which terminate abruptly with no apparent cause might be limited by wrench faults" (Moody and Hill, 1956, p. 1214). The southeast end of the Antelope anticline is apparently terminated by such a fault. This structure is herein referred to as the Antelope terminator fault.

Moody and Hill (1956, p. 1235) state that "apparently boundary faults can 'heal' or lock so that no further movement occurs, and the stresses are then accommodated along other fractures." This seems to be the case with the crustal block immediately northeast of the Antelope structure. This will be referred to as the "Four Bears block" because Four Bears Bridge is located on it.

The Four Bears block is apparently locked onto the block northeast of the Bismarck shear zone and is apparently being dragged along with it. The movement is evidently being accommodated by the Antelope terminator fault. Royse (1967, p. 27) in reference to the Tongue River-Sentinel Butte contact in the upper Fort Union formation states, ". . . the contact can be traced in discontinuous outcrops along Garrison Reservoir to the Four Bears Bridge, west of Newtown, where it is well exposed at an elevation slightly above the bridge abutments. The contact cannot be traced beyond a sag filled with post-Paleocene sediments about 6 miles south of Newtown. Sentinel Butte strata only are present

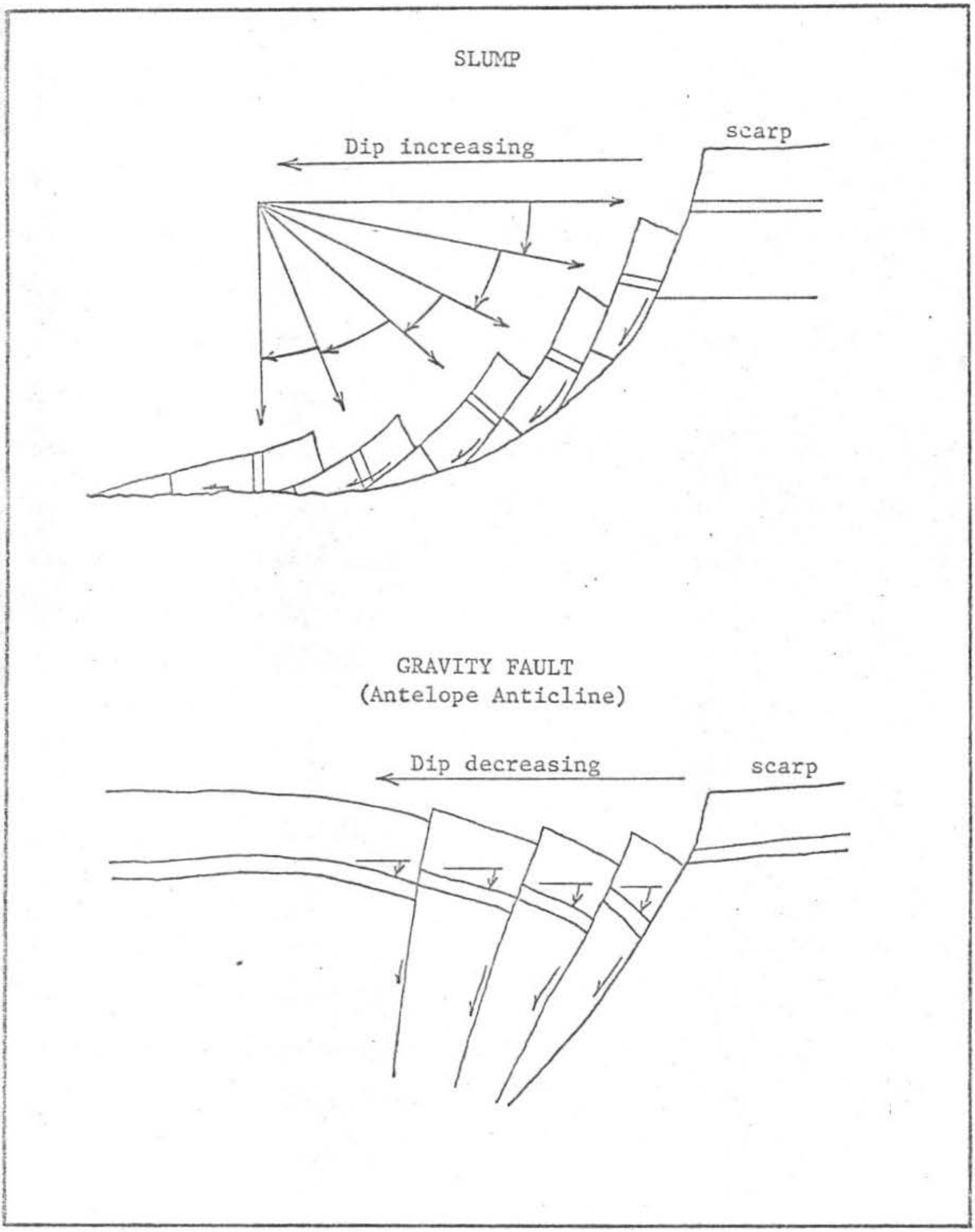

Figure 8.--Comparison of dip in displaced blocks in slumps and gravity faults.

above the reservoir level for several miles south of the sag, and it is inferred that the contact has been displaced downward along a northwest trending fault (Clayton, in preparation)" (Fig. 7). This fault is evidently the southern end of the Four Bears block. The beds south of this fault are downthrown to fill the gap formed by the more rapid movement of the Four Bears block and the block northeast of the Bismarck shear zone to which it is attached.

4. "Gravity faults at the crests of anticlines . . . result from decreased horizontal stress and consequent increased vertical stress" (Moody and Hill, 1956, p. 1211). Such a gravity fault does exist on the crest of the Antelope anticline. This fault is approximately normal to the axis of the structure. It is apparently due to the stretching of the uppermost sedimentary beds along the crest of the anticline during post-Fort Union (Paleocene), pre-Pleistocene time. Glacial till and loess lying on top of the faulted Fort Union in the fault zone are undisturbed.

This fault is at the base of a south-facing scarp in sections 1 and 2, T. 152 W., R. 95 W. (Fig. 8). The tilted blocks at the base of the scarp were at first assumed to be slump blocks. Correlation of strata from shallow bore holes indicated that the dip of beds in the fault zone decreased away from the scarp as would be expected in a gravity fault. The dip in a slump block would increase away from the scarp as reverse block rotation progressed (Fig. 10).

Moody and Hill (1956, p. 1215) stated that "some deep-seated wrenches appear to be indicated at the surface only by systems of small en echelon faults or anticlines."

It is concluded that the Antelope anticline may be a drag fold associated with the Bismarck shear zone.

The Redwing Creek Fault

The Redwing Creek fault is located in south-central McKenzie County about 50 miles southwest of the Nesson anticline (Plate 1). A detailed study of the well logs revealed a high angle reverse fault with a vertical throw of 1200 feet (Plate 2). This structure is buried below the pre-Mesozoic unconformity.

A very minor lineament sub-parallel to the Antelope anticline has been discovered southeast of the Redwing area (Plate 1). Northwest projection of this lineament passes between Shell 22X-28-1 and its offset Shell #1 Turnquist (NE SW, Section 15, T. 148 N., R. 101 W.) 2 miles to the northeast.

Lawson and Smith (1966) describe folding in the continental foreland province in post-Tensleep (mid-Pennsylvanian) time. Deformation was predominantly parallel to the Cedar Creek and Antelope anticlines. Vertical uplift and subsidence on opposing sides of a transcurrent fault parallel to the Cedar Creek-Antelope direction is postulated as the origin of the Redwing Creek structure.

The Fairview Horst

A pair of subparallel lineaments in the southwestern corner of McKenzie County may define transcurrent faults of related deep-seated origin. Projection of these two lineaments into Richland County, Montana, includes the Fairview oil field (Plate 1). The Horse Creek lineament on the northeast trends N. 33° W. and the Bennie Pierre lineament a few miles to the southwest trends N. 36°W (Fig. 3).

Fisher's (1953) surface structure map of west-central McKenzie County, North Dakota outlines two highs between these two lineaments indicating minor tectonic movements during Tertiary time. According to Wallace (1949), upward squeezing of fault zone materials raised sedimentary cover rocks above the San Andreas rift zone. Kingma (1959) described similar structures resulting from wrench faulting in New Zealand. Such a mechanism could account for Fisher's surface highs along these lineaments in McKenzie County.

Available evidence indicates the possible existence of a horst of low relief on the Precambrian surface between the two suggested wrench faults as defined by these surface lineaments.

The Cedar Creek Anticline

The extreme linearity of the Cedar Creek anticline, in itself, suggests a transcurrent fault. Gwynn (1964, p. 192) states, "from the northern-most point where the fold is traceable to the furthest southeast point where it has been found to exist is more than 150 miles." It trends N. 30°W. along its entire length (Plate 1).

Gwynn's (1964) detailed description of the Cedar Creek anticline and related structures is indicative of wrench faulting. He mentions half a dozen domes which indicate cross faulting, several anticlines which could be associated drag folds and an en echelon fault which could be the surface expression of high angle reverse faulting along a parallel wrench fault. He also points out evidence of northeast trending faults which have become apparent with the drilling of deeper oil prospects. These would parallel Sproule's (1962) tectonic trend.

According to Gwynn, the Cedar Creek anticline is characterized by steep dips (30°) and faulting on the west side with shallow dips (1 1/2 to 3°) on the east side. High-angle reverse faults with vertical displacement of nearly a thousand feet have been measured on the Cedar Creek anticline (Davis and Hunt, 1956).

The Cedar Creek anticline appears to be the surface reflection of high angle reverse faulting, along the southwest edge of a long crustal block, which has tilted slightly basinward. The more complicated tectonic province to the southwest, including the Lewis and Clark lineament, the Black Hills Uplift and the Wyoming Couple of Sales (1968), has no doubt also played a role in the origin of the Cedar Creek anticline.

The Foster and Stutsman Highs

The orientation and areal dimensions of the Foster and Stutsman Highs (Ballard, 1963) suggest the segmentation and displacement of a linear Precambrian monadnock or ridge (Plate 1). They could also result from right hand transfer of movement across an intershear block resulting in local uplifts or more simply, just erosional remmants resulting in topographic highs. Thinning in various units over both highs is strongly suggestive of deep-seated tectonic movements (Ballard, 1963).

The Turtle Mountains

It is noteworthy that both the eastern and western flanks of the Turtle Mountains are steep scarps running parallel to the Missouri Coteau escarpment and to the Bismarck and Williston shear zones (Plate 1). The south edge of the Turtle Mountains is also a steep escarpment while the north side slopes gently into Manitoba. Lemke (1960, p. 106) indicates that "the well-defined scarp of the western flank of the Turtle Mountains might reflect a fault scarp," and may reflect tectonic deformation.

The Turtle Mountains may be bounded on three sides by wrench faults. A right hand transfer of left-lateral displacement is indicated (Plate 1). The crustal block on which the Turtle Mountains rest may be cut by an east-west trending fault forming the escarpment on the south. The block southeast of the fault, may be overtaking the northwest block, on which the mountains rest, and underthrusting it, resulting in a minor uplift, or more simply, the Turtle Mountains could be the surface expression of an east-west trending fold which is terminated on both ends by wrench faults (Plate 1).

Meek (1958, p. 19) stated, "faulting known in the Hartney area of Manitoba may be a reflection of the basement instability. The schist underlying the Hartney fault block is thought to be an erosional remmant of a schistose terrane that was protected by down faulting; the movement evident in higher horizons was a result of recurrent movement along this old plane." The Hartney fault lies on the northwest projection of the lineament defining the northeast edge of the Turtle Mountains.

A tectonic origin related to wrench faulting is suggested for the Turtle Mountain uplift. Subsurface information in the Turtle Mountain area does not necessarily support this interpretation.

The lineament defining the west edge of the Turtle Mountains defines the east flank of the Moose Mountains to the northwest in

Saskatchewan. A similar origin is possibly responsible for both of these highs (Plate 1).

The Missouri Coteau

A fault was mapped on the Coteau Escarpment near Avonlea, Saskatchewan by Frazier and others in 1935 (Plate 1). Mollard (1957) cited Kupsch and Wild (1955) as indicating that faults of tectonic origin appear to be responsible for the Missouri Coteau and that lineaments in unconsolidated surficial materials indicate movement during Pleistocene and even Holocene in the Avonlea area. The Avonlea earthquake of 1909 betrays deep-seated motion indicative of transcurrent faulting.

Townsend (1950, p. 1552) investigated "intensely folded and faulted beds" near Lignite, North Dakota, and "found evidence that this deformation may extend to depth or reflect regional structures." Lemke (1960, p. 108) suggests that "the escarpment of the Coteau du Missouri along much of its length may be a fault scarp downthrown to the northeast." Moody and Hill (1956, p. 1215) state that wrench faults are often difficult to recognize because, "the last increment of movement in many cases has been essentially vertical, so that the fault simulates a high-angle normal or high angle thrust fault."

The length of the Coteau Escarpment alone suggests that it may be the surface expression of a major transcurrent fault.

A downthrown block parallels the Coteau du Missouri on its northeast side. Frazier and others (1935, p. 59) stated that, "the regional structure of southern most Saskatchewan, (from the Manitoba border to 50 miles west), is mainly an east or northeast, gently dipping one. It is the west side of a very broad, very shallow trough, the east side of which is in southwestern Manitoba."

Lemke (1960, p. 105) in discussing the structure of the Souris River area stated that, "dips to the northeast appear to be greatest immediately northeast of the escarpment of the Coteau du Missouri, then they flatten out away from the escarpment in a northeasterly direction and rise in the vicinity of the Turtle Mountains."

The Coteau du Missouri appears to be a horst of low relief flanked on the northeast by a broad down-dropped block resembling a shallow graben (Fig. 9). The Coteau Escarpment is apparently the surface expression of the wrench fault between the horst and graben. These two blocks appear to form a hinge line along the continental edge of the foreland (the stable interior). The Coteau block appears to have tilted slightly basinward allowing the block behind it to settle somewhat forming a broad shallow graben (Fig. 9).

The Cavalier High

Ballard (1963) indicated that the Cavalier high was extremely mobile and was expressed as a structural nose of low relief (Plate 1). At various times in geological history it included portions of Cavalier, Walsh, Ramsey, Pierce, Benson and Towner Counties. The lineament pattern in the Turtle Mountain-Cavalier high area shows a distinct anomaly. The structural origin of both features may be linked to intermittent movements along a broadly curved left-lateral wrench fault immediately to the south. This is indicated on the surface by an "s" curve on the southward extension of the lineament defining the northeast edge of the Turtle Mountains (Plate 1).

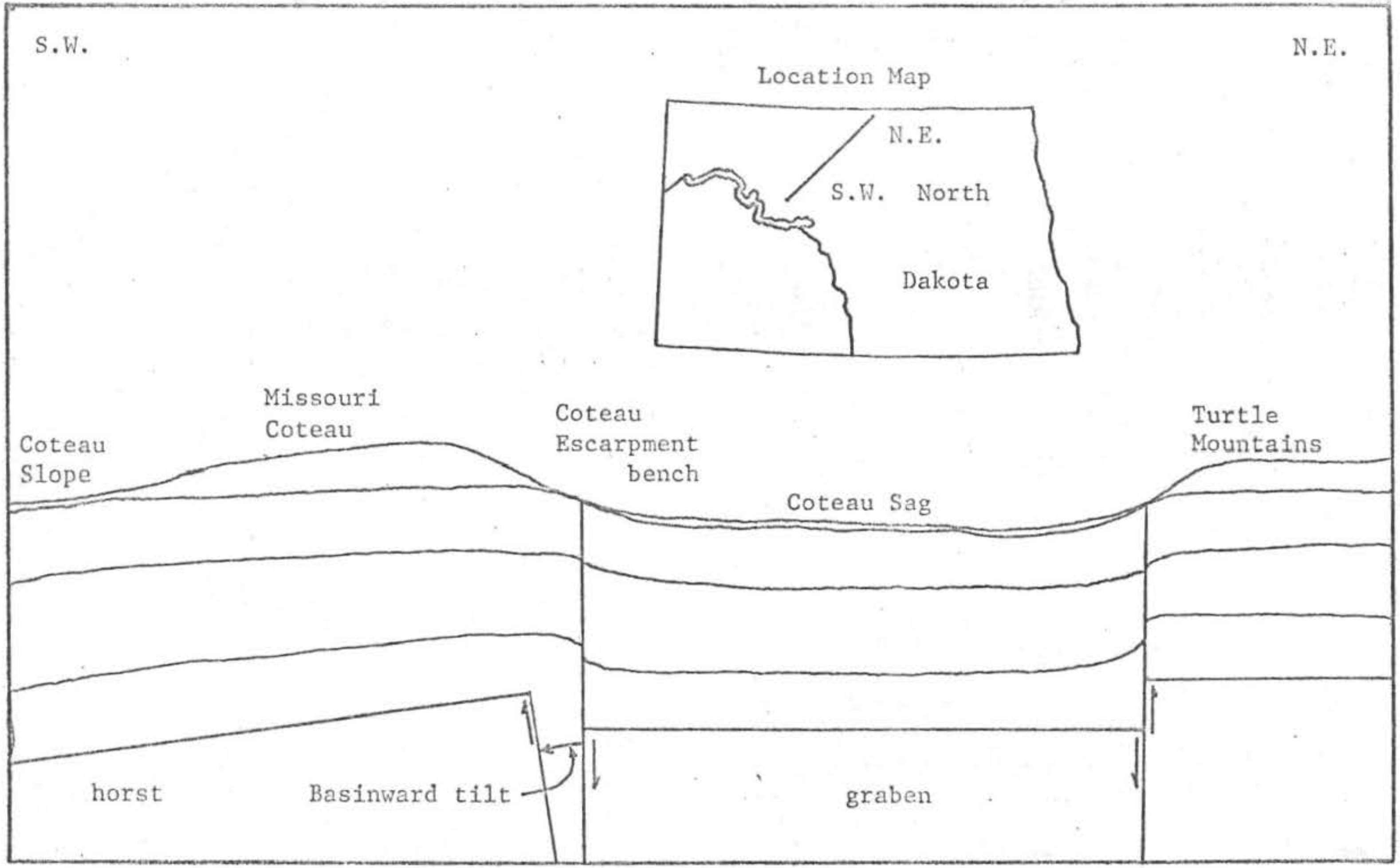

Figure 9.--An interpretation of upper basement structure from the Coteau slope to the Turtle Mountains.

Ballard (1963, p. 33) stated that "the persistent positive nature of the eastern flank highs suggests renewed movement along old structural zones in the Precambrian basement." He noted that growth on these highs was most noticeable during those intervals when the basin depocenter was migrating between southeastern Saskatchewan and northeastern North Dakota. Depocenter migration of this magnetude certainly indicates that the region was undergoing a period of strong crustal stresses. Intermittent minor movements along old zones of structural weakness could be reasonably expected during such a period. It is noteworthy that the zone of basin depocenters (Ballard, 1963, Fig. 8) parallels the Williston and Bismarck lineaments as well as the Missouri Coteau and coincides with the trend of earthquake epicenters (Fig. 10).

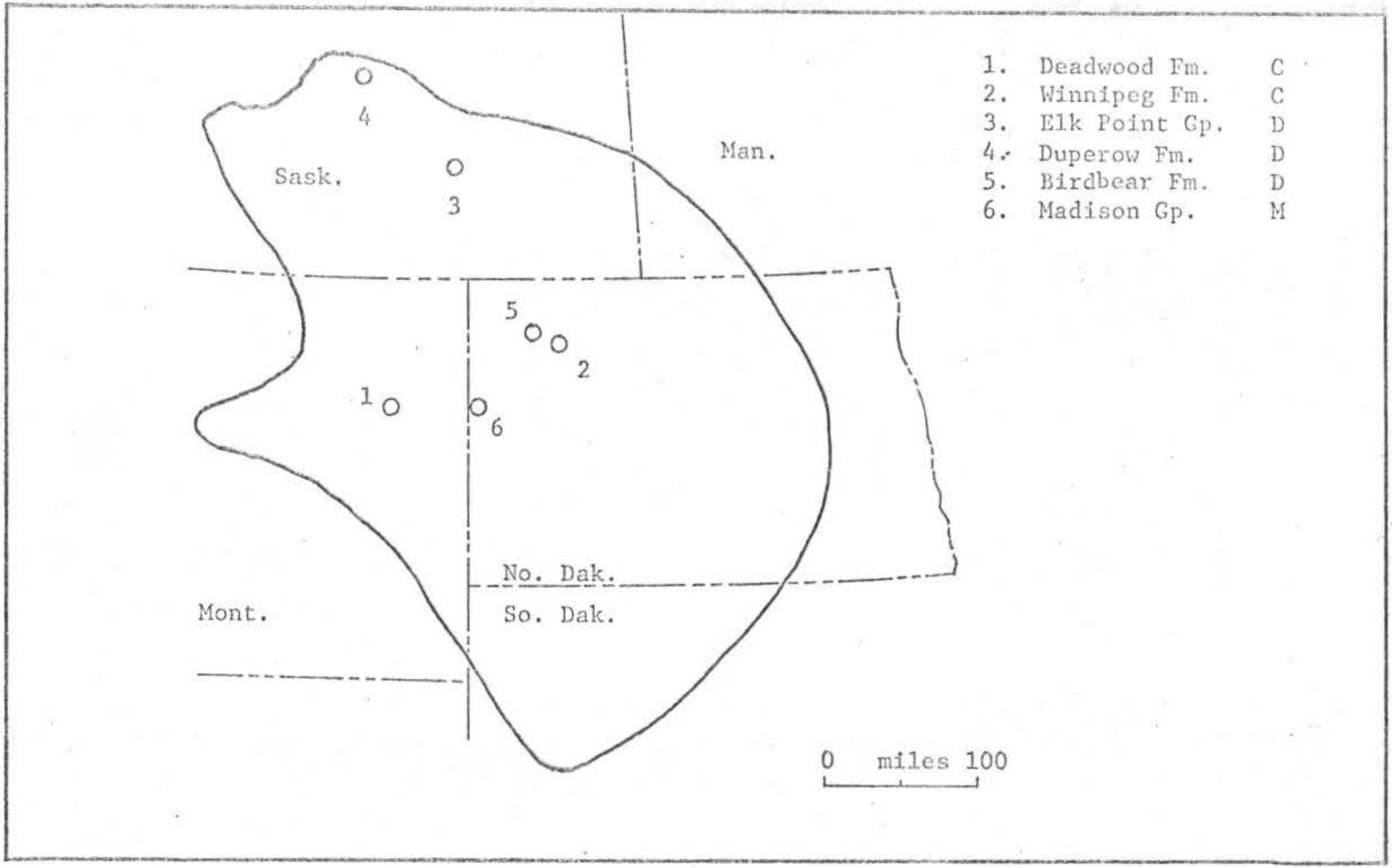

Figure 10. Paleozoic depocenters in the Williston basin parallel the Missouri Coteau and coincide with the trend of earthquake epicenters.

Summary

This study outlines a basic structural framework for the Williston basin. The interpretation as presented is based upon the existence of left-lateral faulting characteristic of the underlying continental foreland fault system as hypothesized. Example structures have been discussed which describe a cross-section of the system from the Cedar Creek anticline on the southwest to the Turtle Mountains on the northeast. The system may be much broader than herein indicated.

Future studies of this nature on various structures within the Williston basin region will gradually fill in the gaps and build a more complete picture or even a new interpretation. No doubt some additional very unusual and interesting structural relationships will be discovered. Study of the fracture pattern and geostructural lineament in North Dakota and eastern Montana has revealed many additional structural anomalies too numerous to discuss in this paper.

Conclusions

1. Lineaments are observable on air photos in the Williston basin.

2. The lineaments apparently reflect the underlying geologic structure.

3. Topographic features such as stream segments, segments of inter-stream divides, elongate lakes, rows of small lakes, sides of buttes and other linear features are parallel to, or offset across, lineaments.

4. A broad left-lateral system of wrench faults apparently underlies the Williston basin region.

5. Most structures in the Williston basin adapt easily to the interpretation of left-lateral wrench faulting.

6. The major displacements in the fault system are apparently Precambrian.

7. Movement parallel to master wrench faults tends to intensify the regional fracture pattern by increasing the overlying joint density.

8. Movement non-parallel to the master wrench faults tends to disrupt the regional fracture pattern with local anomalies.

9. Minor growth, evident in most deep-seated structures, indicates that minor movements have occurred along these wrench faults during the Phanerozoic Eon.

10. The Williston and Bismarck lineaments coincide with a line of modern earthquake epicenters and may be the surface reflection of buried shear zones.

11. Depocenters of many sedimentary units in the Williston basin are located adjacent to the Williston and Bismarck shear zones and may be structurally related to them.

12. The Nesson anticline is apparently attributable to the segmentation and left-lateral en echelon displacement of a Precambrian gneiss zone.

13. The gneiss zone may be the southward extension of the Nelson River gravity high which corresponds to the gneiss zone along the western border of the Precambrian Superior Province in Saskatchewan and Manitoba.

14. The gneiss zone may have trended originally about N. 40° E. but was apparently realigned during the late Precambrian to form its present north-south configuration.

15. The Antelope anticline is apparently a drag fold associated with cross faulting between the Bismarck and Williston shear zones.

16. The Cedar Creek anticline is apparently the surface reflection of high angle reverse faulting along the southwest margin of an elongate crustal block which has tilted 1 1/2° to 3° toward the Williston basin.

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PLATE I
AN INTERPRETATION OF STRUCTURAL RELATIONSHIPS IN THE WILLISTON BASIN
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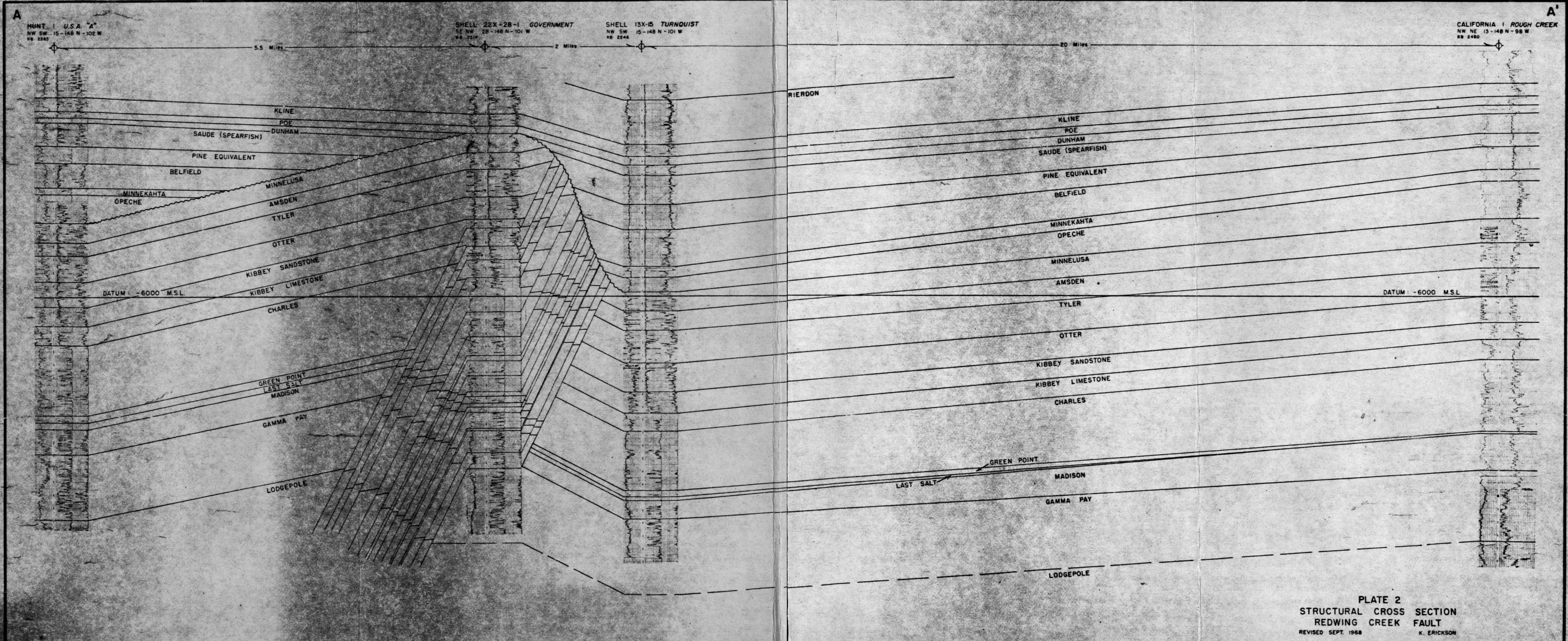

PLATE 2
STRUCTURAL CROSS SECTION
REDWING CREEK FAULT

REVISED SEPT. 1968

K. ERICKSON